Investigation of flexural behaviour of cold-formed steel built-up section beams after exposure to elevated temperature.

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Abstract

Recently worldwide industrial constructions have frequently been built using light gauge materials like cold-formed steel (CFS) sections due to their lightweight and affordable design systems. One important aspect of building design and construction that must be considered is fire safety. However, limited studies are reported on experimental and finite element modelling (FEM) of back-to-back built-up channel sections of cold-formed steel (CFS) under flexure behaviour. Four back-to-back built-up CFS sections were considered for the preparation and the structural performance was investigated. CFS test specimens were exposed to elevated temperatures of 500^{0}C, 600^{0}C and 700^{0}C in an electrical furnace to study the effect of temperature on the structural performance of CFS. The thirty-six FEM models were studied for different web-to-thickness ratios and the results were validated. This paper investigates the load-carrying capacity, bending moment and load mid-span deflection. The study concludes that the load-carrying capacity for flexural behaviour is decreased by 56.04% with reference temperature.

Keywords- *Cold-Formed steel (CFS), Elevated temperature, Flexural behaviour, Finite element analysis, Back-to-back channel.*

1. Introduction

The CFS has been a common principal building material in construction sectors over the last few decades. The CFS comes in thin, slender pieces that have a high strength-to-self-weight ratio, high ductility and a visual aesthetic. The CFS pieces are easily found in the market and have a desired geometry (size & form). The CFS is compared to hot rolled steel sections and other building materials, the cost of construction and the life cycle are more affordable. CFS sections are enough for low- and medium-rise buildings to support the applied load (Kumar et al., 2023). To increase the load-carrying capacity, it is desirable in construction procedures to use back-to-back built-up channel sections as beam and column members (Powell et al., 2023). To meet the demand for infrastructure, manufacturers are using more built-up steel sections. For building techniques, two-channel sections that are bolted or welded together in a built-up configuration are favoured.

CFS buildings are more vulnerable to fire and its aftereffects. One of the weakest risks that seriously deteriorates steel structures is fire, which can occur during building accidents. Consequently, a greater understanding of the CFS elements' structural behaviour during fire aids structural engineers in their design work. In previous research projects, back-to-back CFS beams under four-point loading at room temperature were thoroughly studied both experimentally and numerically.

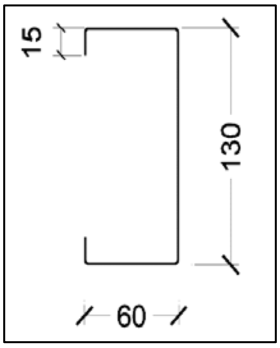
Wang (2010) investigated an experimental and numerical investigation on cold-formed steel C-section flexural members at room temperature. It concluded that local buckling, distortional buckling, and interaction between local and distortional buckling were observed in the pure bending and non-pure bending tests. None of the specimens failed in lateral–torsional buckling. Muftah (2015) investigated the mechanical properties of the CFS at post-elevated temperature, the temperature varies from 200^{o}c to 1000^{o}c. It concludes that all weights measured before and after heating for all temperatures are the same and the Elastic modulus of the CFS is decreased by 75 % of its original elastic modulus when exposed to high temperatures.

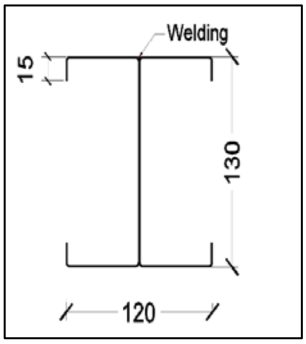
Most of the investigation and findings on mechanical properties of CFS specimens at elevated temperatures. Zhen (2022) investigated a study on the mechanical properties of cold-formed steel at elevated temperatures ranging from 20 to 700°C. It studied the parameters like yield strengths, ultimate strengths, the elasticity modulus, and the stress-strain curve. Kankanamge and Mahendran (2011), investigated a study on a rapid reduction in mechanical properties such as yield strength and elastic modulus under fire conditions. It is concluded that there is no clear relationship between the elastic modulus and the steel grade or thickness. Kumar et al. (2023), conducted a study on post-fire flexural behaviour of cold-formed steel built-up ‘I’ sections beam under unrestrained conditions. It concluded that the moment carrying capacity of the specimen is decreased due to elevated temperature.

Following an extensive study of the literature, the following research gaps are noted. A few research works carried on the flexural behaviour of CFS back-to-back sections at high temperatures. More research has been carried on the raised temperatures, and physical changes of CFS built-up beams subjected to conventional fire. Also, there is a lack of experimental and finite element analysis data on the CFS section exposed to high temperatures during flexure behaviour.

1.1 An experimental summary of the investigation

This study investigates the post-fire flexural behaviour of steel beams that have been cold-formed and built up to high temperatures. For the experiments, back-to-back built-up specimens were welded together. Steel beams were heated to various temperatures 500^{O}C, 600^{O}C and 700^{O}C in an electrical furnace. The load-carrying capacity of the CFS section are assessed in this study. The influence of heating modes is understood by noting physical changes. Failure patterns were discovered and contrasted with the outcomes of the experiment.





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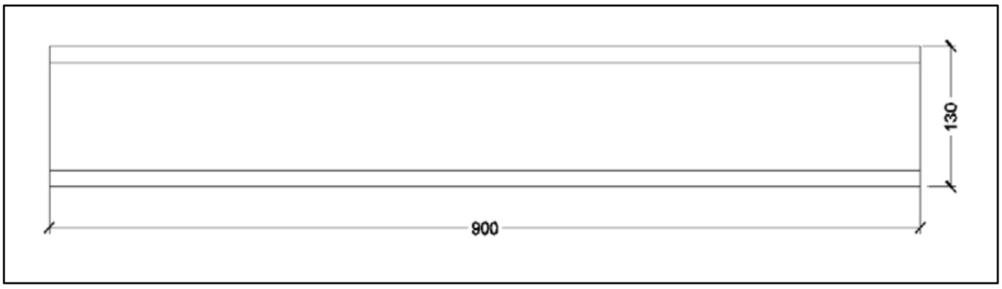


c)

Fig. 1 Section geometry of built-up sections (a) Single channel section (b) Built-up ‘I’ section (c) Sectional view of the specimen.

2. Experimental Investigation

2.1 Specimen details

This research employs the C-section with lips from the locally accessible steel industry based on the needed dimension. The section has a web that is 130 mm deep, a flange width of 60 mm, a lip piece that is 15 mm deep, and components that are 1 mm thick. The specimen is 900 mm in length. An electric arc weld joint was used to link the CFS C section as a back-to-back built-up segment to prevent the stiffness from being reduced (Kumar et al., 2023). In fig. 1 shows the cross-sectional dimension and length of the specimen.

2.2 Measurement of initial geometric imperfections

The cold roll forming technique first bends the sheet into the desired shape, and then the electric arc welding procedure joins the two pieces as a back-to-back built-up section. The section's original geometric flaws resulted from the welding and manufacturing processes, which might have an impact on the CFS section's buckling behaviour and other failure modes. Each test specimen's initial defect is measured. The specimen's nominal and measured dimensions are shown in Table 1. Eight different specimen areas were used for the measurements.

Table 1: Measured dimension of CFS channel beam.

Measured dimension of specimens in mm.					
No.	Web	Flange	Lip	Length	Thickness
A1	130.5	60.3	15.1	900.2	1.01
B1	129.2	58.0	14.8	899.1	1.01
C1	131.1	60.8	15.1	903.2	0.95
D1	130.0	60.3	16.2	896.2	1.00
Avg.	129.9	60.2	15.3	900.1	0.99

2.3 Elevated temperature test on CFS sections

The constructed CFS specimens were heated using a computerised electrical furnace, as seen in Fig. 2. The specimen is kept at a constant temperature throughout thanks to the furnace's thoughtful construction. Following ISO 834 standard fire curves, which are as follows: 5 min (500 ^{O}C), 10 min (600 ^{O}C) and 15 min (700 ^{O}C) respectively, were used to heat all the steel beam specimens. The furnace cooling procedure was used at this time, and the specimens were allowed to cool naturally (furnace cooling method) at room temperature.

Fig.2 Electric furnace.

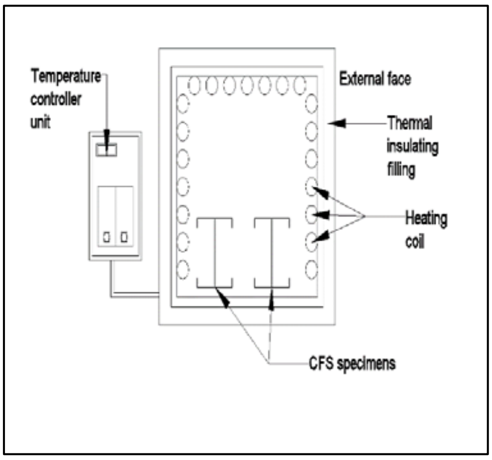


Fig.3 Beams in furnace.

3. Finite element modelling

3.1 General

The non-linear elasto-plastic analysis of cold-formed steel built-up beams were modelled to simulate flexural behaviour using finite element software ABAQUS [Kumar et al., 2023]. The model was based on centre-line dimension of cross-section. Specific modelling issues are described in the following section.

3.2 Geometry and material properties

The test set-up was modelled for both flexural as shown in figure. The material properties such Young's modulus (E), strain, poisson's ratio, yield stress (fy), ultimate stress (fu) is assigned. According to past research to find more accuracy the element mesh size considered for cold-formed steel back-to-back channel specimens is 5 x 5 mm^2 to 10 x 10 mm^2. The SR4 element was used for meshing. To generate the weld connection in the numerical model between the channel sections, an independent mesh fastener with a weld option is adopted from ABAQUS.

a) b)

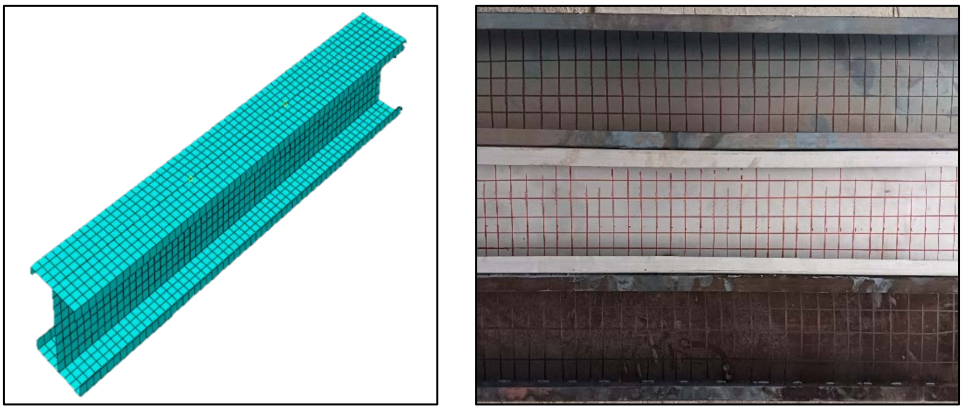


Fig. 4 Meshing on specimens a) FEM b) Experimental

3.2 Loading and boundary conditions

To simulate the exact experimental set-up the channel beams are connected by using surface-to-surface contact option. The simply supported boundary condition is applied at the supports of specimens. For flexural behaviour of specimens, the two-point loads are placed 130 mm apart from the centre and in the case of web-crippling behaviour the vertical loading was applied on the centre of the CFS beam. To generate the loading effect horizontal displacement U1 and longitudinal rotation UR3 were restricted at the ends of the flange as well as the mid-point of the web and two supports of points. Vertical displacement U2 was restricted along the height of the flange at two support points for flexural behaviour, while longitudinal displacement U3 was restricted only at mid-point of the web of one of the supports. In proposed FE study, the general-static (STATIC) analysis method is adopted.

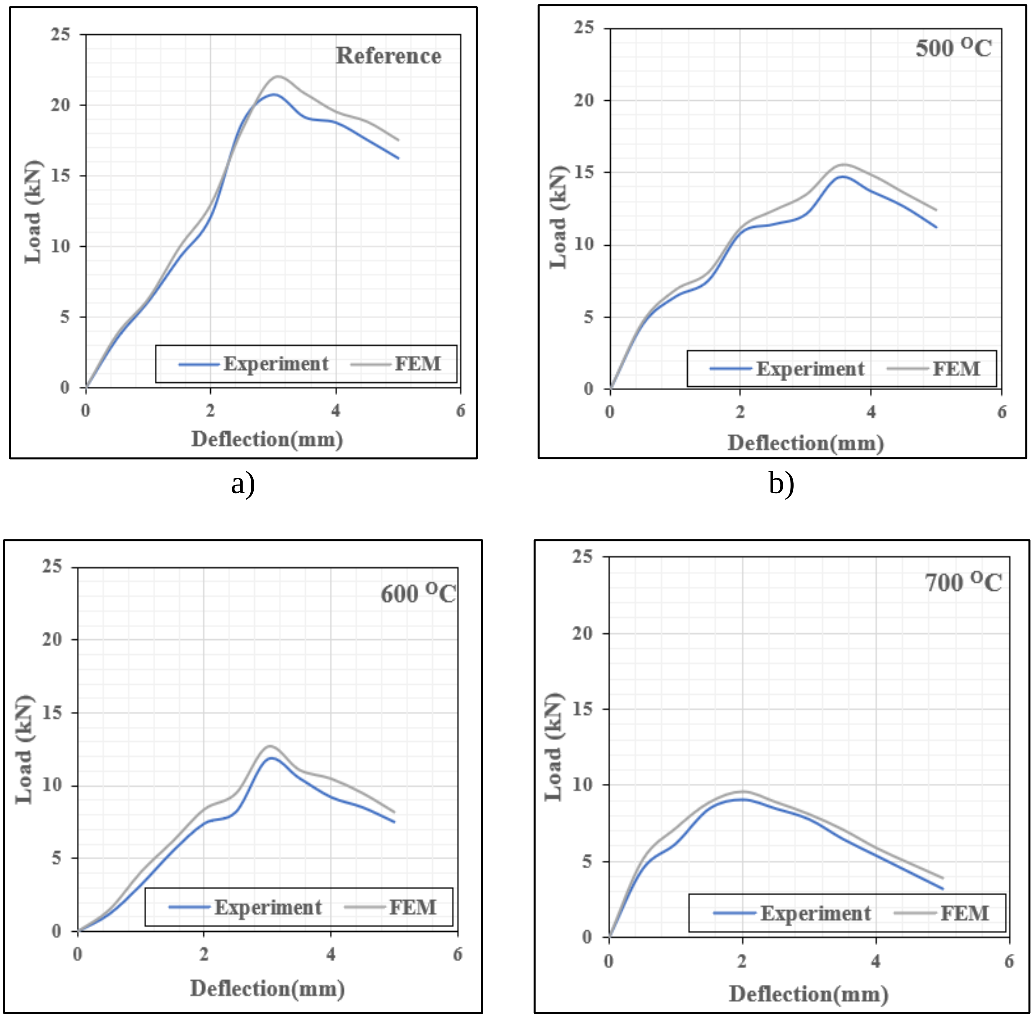
Table 2

Comparison of experiment and finite element results of flexural behaviour.

SR NO.	Temperature (Degree cent.)	Experiment	FEM	P_{EXP}/ P_{FEM}	% Deviation
		Load (kN)	Load (kN)		
1	0^0C	20.70	21.9	0.945	5.47
2	500^0C	14.65	15.54	0.948	5.72
3	600^0C	11.80	12.7	0.928	7.08
4	700^0C	9.10	9.60	0.947	5.20
Mean	-	-	-	0.942	-

3.3 Verification of finite element model

To validate the finite element model, experimental loads are compared with finite element analysis. The main objective of this comparison was to verify and check the accuracy of the finite element model. The table 2 shows that comparison of test results (P_{EXP}) with numerical results (P_{FEM}) of flexural behaviour. Load-deflection curves comparing the experimental results and the finite element results are shown in Fig. 5. The mean value of the P_{EXP}/P_{FEA} ratio is 0.942. A maximum difference of 5% to 7.5% was observed between the experimental and the numerical results.



a) b) c) d)

Fig.5 Comparison of Load vs Deflection for experiment and FEM of flexural behaviour specimens.

4. Result and discussion

4.1 Physical observation

4.1.1 Change in colour and surface pattern

The following Fig. 6 shows the colour change and damage observed in specimens. The 500^{O}C and 600^{O}C specimens turned dark blue for the were subjected to the temperature. In the case of 700^{O}C, the specimens turn with brown colour patches.

Fig.6 Colour change of 500^{O}C, 600^{O}C, and 700^{O}C specimen.

4.1.2 Weight change

The cold-formed weight change parameter is crucial for determining if any chemical alterations or structural disruptions have occurred that might be causing the weight to change. This study shows that the weight of the beam changes noticeably as it is heated.

4.2 Failure behaviour

Every steel beam underwent testing until failure mechanisms and specimen failure were noted. The length of exposure and the corresponding change in temperature magnitude determine the specimen's failure mechanism. Lateral Torsional Buckling (LTB) was the main failure that was seen throughout the trial. There were two different kinds of failure modes found during testing; one is local buckling and another is lateral torsional buckling

a) b)

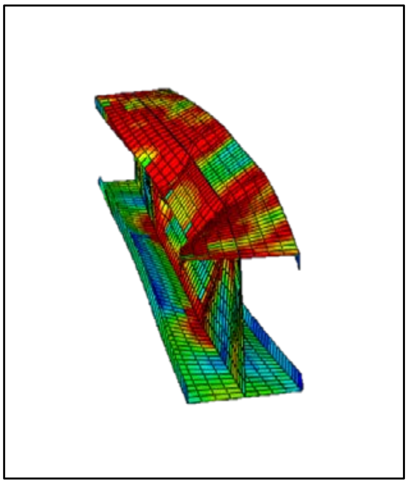


Fig. 7 Comparison of experimental and numerical behaviour at failure for specimen. a) Experimental and b) Numerical

5.0 Parametric study.

After completing the validation process, a detailed parametric study was developed to investigate the flexural behaviour of the CFS built-up 'I' section beam under various temperatures. Therefore, 36 non-linear FE models were developed with consideration of different geometrical parameters including three sections the dimensions of one channel are 150 X 60, 175 × 60 and 200 X 60 with section thicknesses (t) of 1 mm, 1.5 mm, and 2 mm. Moreover, this study has incorporated the effect of web slenderness ratio (d_1/t) ranged from 37.5 to 200, angle between plane of web and plane bearing surface ϴ=90^O, ratio of bearing length to flat dimension of web is less than 1 for temperature range 500^{O}C, 600^{O}C and 700^{O}C.

Table 3. Detailed parametric study plan for flexural behaviour.

Dimension of one channel (mm X mm)	Thickness (mm)	Temperature (Degree cent.)	Yield strength (fy) (MPa)	No. of models
150 X 60	1	500	415	12
175 X60	1.5	600	415	12
200 X60	2	700	415	12

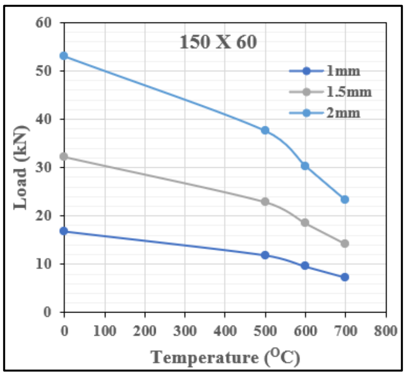
The following table no. 4 shows the load-carrying capacity of flexural specimens of length 1000 mm. The two-point loads are placed 150mm apart from the centre. The 36 FE model are developed for flexural behaviour.

Table 4. Detailed parametric study results.

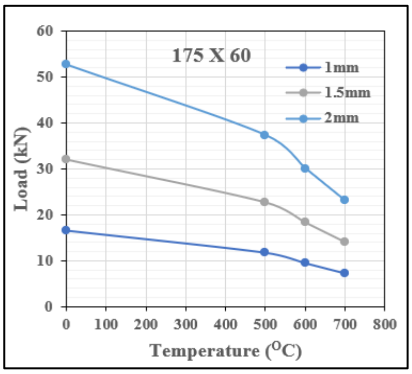
Sr. No.	Dimension of one channel (d x bf) (mmxmm)	Thickness (mm)	Temperature (Degree cent.)	Load carrying capacity (kN)
1	150 X 60	1.0	0	16.71
2	150 X 60	1.0	500	11.85
3	150 X 60	1.0	600	9.56
4	150 X 60	1.0	700	7.32
5	150 X 60	1.5	0	32.27
6	150 X 60	1.5	500	22.87
7	150 X 60	1.5	600	18.45
8	150 X 60	1.5	700	14.14
9	150 X 60	2.0	0	53.01
10	150 X 60	2.0	500	37.58
11	150 X 60	2.0	600	30.32
12	150 X 60	2.0	700	23.23
13	175 X 60	1.0	0	16.63
14	175 X 60	1.0	500	11.79
15	175 X 60	1.0	600	9.51
16	175 X 60	1.0	700	7.28
17	175 X 60	1.5	0	32.03
18	175 X 60	1.5	500	22.7
19	175 X 60	1.5	600	18.32
20	175 X 60	1.5	700	14.03
21	175 X 60	2.0	0	52.62
22	175 X 60	2.0	500	37.3
23	175 X 60	2.0	600	30.09
24	175 X 60	2.0	700	23.06
25	200 X 60	1.0	0	16.65
26	200 X 60	1.0	500	11.8
27	200 X 60	1.0	600	9.52
28	200 X 60	1.0	700	7.29
29	200 X 60	1.5	0	32.72
30	200 X 60	1.5	500	23.19
31	200 X 60	1.5	600	18.71
32	200 X 60	1.5	700	14.34
33	200 X 60	2.0	0	54.49
34	200 X 60	2.0	500	38.63
35	200 X 60	2.0	600	31.16
36	200 X 60	2.0	700	23.88

Note: d = overall depth of the section and bf = width of the flange.

Fig. 8 shows the load-carrying capacity of specimens for various temperatures with different types of section sizes and different types of thicknesses of one channel 1mm, 1.5mm and 2mm respectively.



(a)



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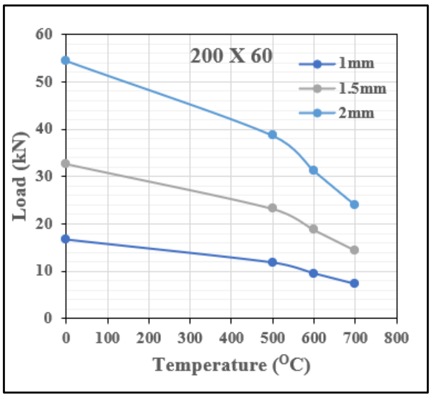

(c)

Fig.8 a) Load-carrying capacity of section 150 X 60. b) Load-carrying capacity of section 175 X 60. c) Load-carrying capacity of section 200 X 60.

6. Conclusion

This paper conducted an extensive numerical analysis to investigate the flexural behaviour of cold-formed steel-built beams after exposure to temperature. A finite element analysis considering initial geometric imperfection and material non-linearity was developed to analyse simply supported cold-formed steel beams. The finite element analysis predicted the load-carrying capacity, load-mid-span deflection these predictions were verified against experimental results. In a parametric study, total thirty-six cold-formed steel beams are modelled, with considering different web height to thickness ratio and various temperature. Based upon the experimental results the load-carrying capacity for flexural behaviour specimens are reduced 56.04% after exposure to elevated temperature.

In FE investigation, web height to thickness ratio showed that the significant increase in average web crippling strength of specimens. Magnitude of temperature on CFS specimen has a greater contribution in reducing load-carrying capacity. The weight was measured for every temperature specimen both before and after heating is same.

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Data availability The authors declare that data supporting the findings of this study are available within the paper.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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